

A METHOD FOR SYNTHESIZING SEDIMENTARY STRUCTURES
GENERATED BY MIGRATING BEDFORMS

by

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Submitted to the Department of Earth and Planetary Sciences
on March 31, 1978, in partial fulfillment of the requirements
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ABSTRACT

This study presents a new method for artificially synthesizing sedimentary structures. The method involves the combination of a series of sediment-bed-surface profiles into a qualitative representation of internal bed structure. Several previous studies which have been made of the relationship between bedforms and sedimentary structures have been limited by various aspects of the nature of the studies. This method has the advantage of being a laboratory technique, but overcomes the usual spatial constraints of laboratory studies, through the use of mathematical manipulation of the data.

In addition to an exposition of the method, several tests are included, which show a qualitative agreement between structures created synthetically and structures actually formed in flumes and natural environments.

Although there is no completely infallible test of the technique, the excellence of the agreement of the tests made indicates the validity of the method.

Thesis Supervisor: John B. Southard

Title: Associate Professor of Geology

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INTRODUCTION AND HISTORY

Since geologists first started looking critically at sedimentary rocks, they have been intrigued by the sedimentary structures found in the strata. This paper is the presentation of a new method for the artificial synthesis of these sedimentary structures.

Sorby, one of the earliest workers in the field of experimental sedimentology, discovered that a relationship existed between bedforms observed in an alluvial channel and sedimentary structures formed in sediment in the channels (Allen, 1963a). Since that time, much work has been done with the bedforms themselves, and with sedimentary structures, but little relating the two (Harms, 1969). It is the purpose of this paper to demonstrate the testing and use of a new experimental technique which will allow this relationship to be more fully studied in a direct manner. Until the present time, the only flume studies of internal structures have been based on sections taken in flumes after the beds had been drained (Brush, 1958; McKee, 1957), or on photographs taken through the clear side walls of the flume (Jopling and Walker, 1968; Simons, et al., 1964; Southard and Harms, 1972; Simons et al., 1965; Middleton, 1965). The method presented here uses an artificial technique to synthesize internal structures. These structures are created from the combination of a series

of sediment bed surface profiles taken over a period of time. The internal structures can be directly related to the bedforms which created them, since the technique is applied to real-time study of the bedforms and structures involved.

The earlier flume studies involved running the flume to equilibrium, analyzing the bedforms present, draining the flume, and then drying and sectioning the bed (McKee, 1957). This is a slow process, requiring long waiting periods for the sand to dry sufficiently to permit sectioning. From personal experience, it may be stated that this process can consume days for each run. Other studies, using side-wall photographs (Jopling and Walker, 1968; Middleton, 1965), are restricted to a longitudinal profile along the wall of the flume -- an area that can be demonstrated to be affected by boundary effects. In addition, the majority of flume studies are run at a zero aggradation rate -- meaning that there is no net buildup of the bed. Since no net buildup occurs, the majority of sedimentary structures are erased by reworking of the sediment by successive bedforms. The only structure preserved, and visible in section cuts made after the flume run is completed, is that in very deep troughs and that created by the last bedform to pass the sampling station. In the studies which have involved aggradation, either climbing ripples were produced (Southard and Harms, 1972; Jopling and Walker, 1968; McKee, 1965) or artificial deltas were constructed (Jopling, 1960; McKee, 1957;

Jopling and Walker, 1968). The climbing-ripple studies produce structures similar to those found in low-energy, high-sediment environments such as river flood plains and areas of overbank flow (McKee, 1966), or areas of glacial sedimentation (Jopling and Walker, 1968). While these are nature environments, they are extreme examples of a common situation. The conditions which produce high-angle climbing ripples studied are not representative of all environments in which ripples are found, or in which ripple-produced stratification could be expected to form. In fact, most stratification believed to be produced by ripples must be created by "climbing ripples", but the sedimentation rate, and therefore the angle of climb, is so low that the stratification produced does not resemble the classic "ripple-drift cross-lamination." The artificial delta studies have been largely concerned with the description of how bedding originates (Jopling 1960, 1965; McKee, 1957). These have determined what processes lead to the inhomogeneity of sediment which we see as bedding, but they have little applicability to the determination of diagnostic flow phenomena present when the strata were deposited. What is necessary, therefore, is a procedure through which the actual production of internal structures by ripples (and other moving bedforms) can be directly observed and studied. While it is possible to do this by adding sediment to the flume, thereby causing aggradation and building up the bed to create internal structures, the difficulties involved in this process are large. For example,

the regulation of the addition of sediment into the flume is very important, but it is hard to do this accurately. The fact that it is desirable to apply the technique to studies in a standard laboratory flume eliminates the possibility of studying structures produced by dunes. The scale of dunes, the bedforms they produce, and the flow depths necessary to produce them, exceeds the size (depth and width) of common laboratory flumes if internal structures are to be produced. The result of this is that the technique will only be applied to ripples in the present work.

II. STUDIES OF NATURAL FLOW ENVIRONMENTS

Another avenue along which the study of the relationship between bedforms and internal structures has proceeded is the study of natural flows. These studies have ranged from classification systems for cross-stratified deposits (Allen, 1963b) to large-scale studies of sedimentary structures deposited by rivers and other natural flows (Harms and Fahnestock, 1965; Coleman and Gagliano, 1965; Imbrie and Buchanan, 1965; Harms, et al., 1962; Doeglas, 1962; Coleman, et al., 1964; McKee, 1957a). These studies have drawbacks which limit them in their capacity to give us interpretational abilities. They have been restricted to conditions in which the flow dries up to expose the sediment bed to scrutiny. While this is not a major impediment, it does limit the number of environments

which can be studied directly. In some cases (Doeglas, 1962) the river being studied is not even flowing at the time it is being studied. This creates a certain margin for error in any assumptions made about the relationship between the bedforms observed in the dry channel and the flow which created them. In other cases, the structures studied lie near an active channel but are (obviously) not under water at the time of sectioning (Harms and Fahnestock, 1965; Harms et al., 1962). What these studies of natural situations do yield is a picture of what types of bedforms are found in "real" streams (as opposed to flumes) and what kinds of sedimentary structures are found in present-day natural environments. It is important to realize that the data taken from flumes compare well with data from natural environments. When the data points from carefully selected natural cases (chosen to eliminate the effects of unsteadiness) are plotted with flume data, there is a good match of points (Harms, et al., 1975). This means that flume data are "as good" as data taken from natural situations, but are limited by the effects of the scale of flumes currently available.

III. SIGNIFICANCE FOR THE STUDY OF SEDIMENTS

It should be understood that one purpose of this analysis of how bedforms create sedimentary structures is the interpretation of ancient sediments. If we have some idea of how

certain sedimentary structures are formed, or how they vary under different conditions of flow, then it may be possible to determine what flow conditions existed at the time of deposition of a sediment bed containing those structures. Several attempts at such an environmental reconstruction have been made, most using comparisons with present-day environments as guides, (Cotter 1971; Masters, 1967; Pelletier, 1965; Harms, et al., 1975). These have, in general, been limited to determinations of paleoslope, general direction of regional flow, or general depositional history (based more on stratigraphy than on sedimentary structures). The limitations on these rock studies are more in the lack of present-day comparison than in collection of data from outcrops and drill cores. There is one aspect of the relationship between modern-day sediments and sedimentary rocks which should be carefully considered in any comparison between the two. The rocks have undergone a certain degree of compaction, and this effect must be taken into account when comparing the dip angles of cross-bedding in ancient rocks and modern sediments. Füchtbauer and Müller (1970) give an equation for the alteration caused by this effect:

$$\tan \alpha_o = \frac{\tan \alpha \times 100}{60 + P}$$

Where α is the measured dip, P the porosity in percent, α_o is the original dip, and the original porosity is assumed to be 40 percent. The porosity is determined by the study of

thin sections, which reveal the amount of cement filling pore spaces in the rock. In addition, through the dissolution and removal of rock material, as happens in stylolites, for example, the angles can be diminished even farther than through simple compaction (Füchtbauer and Müller, 1970). This effect may have a sizeable impact on quantitative comparison of ancient and modern sediments, where the measurement of the angle of dip of cross-bedding is involved. What is really needed, then, is a method of producing sedimentary structures from bedforms under a wide set of well defined flow conditions. This would yield a catalog of bed structures which could be compared to the features observed in the field to provide a more complete picture of what flow conditions existed at the time of deposition of a certain bed.

IV. ANALYSIS OF PREVIOUS STUDIES

All of the studies mentioned, both flume and "outdoor", have provided us with some information on what types of flow produce what bedform and, in turn, what bedform produces what structure. Added together, this gives us a method of proceeding directly from flow conditions to sedimentary structures. Harms (1969) has provided an excellent summary of the flow conditions which produce ripples, and the changes which occur in ripple geometry due to changes in flow conditions. In general, low-energy flows produce ripples with uniform height

and spacing, continuous but sinuous crests, and asymmetric, angular profiles with the downstream face sloping at the angle of repose of the sediment. As the energy of the flow increases, crests become shorter and more curved and the height and spacing become less regular. Knowing this relationship between flow energy and ripple geometry allows the shape of a ripple to be interpreted in terms of the flow intensity which created that ripple. In addition to flow intensity, ripple geometry can also indicate whether the flow was unidirectional, oscillatory, or a combination of the two. Oscillating flows produce more rounded ripples, more symmetrical in cross-section, with long, straight crests and uniform height and spacing (Harms, 1969). A further refinement of the relationship defined by Harms is related by Southard (1971): in plotting the data from a series of flume runs (Simons, et al., 1961) Southard constructed a series of depth-velocity-size diagrams which define the flow conditions under which ripples would be expected to form. Although the general sequence: flat bed (no movement)-ripples-dunes-transition-upper flat bed-anti-dunes with increasing flow strength had been described earlier (Simons et al., 1961), Southard was the first to provide a graphic representation which allowed a definite one-to-one correspondence between bedform and flow strength. It should be noted here that the mode of sediment transport changes as flow strength increases. In the lower flow regime, where ripples and dunes ("megaripples") form, transport is in discrete steps, the

particle motion is intermittent, form roughness is the predominant bed roughness, and the sediment concentration is 10-2000 ppm. In the upper flow regime, particle motion is continuous, grain roughness predominates, and the bed material concentration is 2000 ppm and up (Reineck and Singh, 1975; Harms and Fahnestock, 1965). In the upper flow regime, the upper flat bed and antidunes are the predominant bedforms (Middleton, 1965). According to Guy, et al., (1966) ripples form at velocities of 20 to 40 cm/sec for sands with a median diameter of 0.45 mm. For sands with median diameters of 0.19, 0.27 and 0.28 mm, the range of velocities was 20 to 50 cm/sec. Above a median diameter of about 0.7 mm, ripples do not form, with dunes being the first bedforms to appear on the flat bed (Southard and Boguchwal, 1972). All of these are at flow depths between 9 and 35 cm. With this detailed picture of what flow conditions cause ripples to form, we can now go on to look at what sedimentary structures are formed by moving ripples.

The structures created by ripples are similar to those created by dunes, but on a smaller scale. Dunes ("megaripples") are defined as bedforms with a height in excess of 10 to 20 cm (Harms et al., 1975) and a spacing of 60 cm to several meters (Reineck and Singh, 1975). Ripples are smaller, with spacings usually less than 30 cm (Reineck and Singh, 1975) and heights on the order of a few centimeters, with a height to spacing

ratio of about 1:10 (Harms, et al., 1975). When these bedforms occur in situations in which sedimentary structures are formed, they commonly create "trough" cross-stratification (Harms and Fahnestock, 1975). The smaller scale stratification formed by ripples is called "rib and furrow" when viewed on a horizontal plane (Harms et al., 1975), and trough/trough cross-bedding when seen in three dimensions (Füchtbauer and Müller, 1970). The shape of the cross lamination is generally spoonlike in character, with the points of the spoons facing downstream, and the bowl of the spoon concave up (Harms and Fahnestock, 1965). The dimensions of these features are similar to those of the ripples that formed them, with thicknesses of about 2-3 cm, with a trough radius of about 20 cm (Reineck and Singh, 1975). It is assumed that these structures are formed by the infilling of scours by moving ripples (Harms and Fahnestock, 1965), with the "hole" produced by one ripple filled in by the next. Although this mechanism was not fully understood in the past, the present work shows the correctness of that assumption.

V. USE OF RIPPLES TO INTERPRET FLOW CONDITIONS

In natural settings, ripples are formed in most sedimentary environments where fine-grained, noncohesive sediments are found. It is, perhaps, unfortunate that ripples are so ubiquitous, because this limits their use as a diagnostic tool. Sedimentary structures attributable to ripples can be found in

many environments, such as: sandy intertidal flats, shoals, fluvial sediments (upper point bars, levees), deep-sea sediments and, to a lesser degree, lacustrine and fluvioglacial sediments (Reineck and Singh, 1975). Also, while there are geometric differences in the flows producing them (Harms, 1969), these differences are generally so small that they are masked by differences between single ripples in a ripple chain (Harms, et al., 1975). The best use of ripples as a diagnostic feature may be in combination with other elements of stratigraphy. In examining the sedimentary record, the presence of ripple-generated structures does give a definite picture of the flow conditions existing at the time of deposition (especially when applied to a depth-velocity-size diagram such as Southard's). Combining this information with other interpretive aids, such as stratigraphic sequence, can define an environment of deposition rather fully (Harms et al., 1975). All this implies that being able to define what structures are produced by migrating ripples can at least allow us to determine a general picture of what flow conditions existed at the time of deposition. We have been, however, seemingly limited to examining natural cases, in which our knowledge of the flow conditions is incomplete, or else flume conditions, where our ability to construct real sedimentary structures is limited by the physical dimensions of the flume itself.

VI. A NEW TECHNIQUE FOR PRODUCING SYNTHETIC SEDIMENTARY STRUCTURES

This brings us to the establishment of a new technique for the synthesis of internal sedimentary structures by ripples. The technique involves a simple arithmetic "transformation" of data taken from flume runs, and it produces synthetic stratification which qualitatively duplicates structures formed under "natural" conditions. The advantage of this new technique is that it does not require lengthy studies of natural streams, yet it produces sedimentary structures which are not as severely limited by the dimensions of the flume.

The technique has a very simple physical foundation. In nature, sedimentary structures are simply the buried remnants of bed surfaces. Under natural conditions, aggradation occurs, so the bed is slowly built up. In this process, some portions of the bed surface are buried and preserved. The surface as preserved represents a profile of the bed at one specific moment in time. In the synthesis technique, a series of profiles of the surface of the bed of the flume are taken at uniform intervals over a period of time. These profiles, taken across the flume, perpendicular to the flow direction, or along the flume, parallel to the direction of flow, are then combined to produce a representation of internal structure in the bed. This representation is qualitatively similar to actual cross

sections, as seen in photographs made of sections cut in flumes and natural channels.

One advantage of the technique is that a simple arithmetic "transformation" can be made on the profiles. In effect, this transformation lowers the datum of measurement for each profile, relative to the preceding one. This reproduces the natural process of aggradation, in which each succeeding bedform rides over a bed made slightly higher by aggradation. This process can produce, by a synthetic technique, ripple cross-bedding similar to that seen in nature. A further advantage is that a variety of "transformations" can be applied to the profiles taken from a single flume run. Each new "transformation" represents a different rate of buildup, or aggradation, of the bed. In this way, a whole group of aggradation rates can be synthetically applied to a single flume run with one set of flow conditions. In addition, flow conditions can be altered from one flume run to the next and the changes (if any) in the artificial structures produced can be noted. The ability to carefully control the flow conditions in a flume allows accurate comparison of changes in structures to changes in flow conditions. The technique also allows the manipulation of data so that the synthetic stratification produced in the flume can be compared qualitatively with stratification produced in natural environments. What follows is a description of the technique, a test of its verisimilitude, and an

application of it to a real case.

I. DESCRIPTION OF THE FLUME

The experimental channel used for this study is a flume located at the Laboratory for Experimental Sedimentology at the Massachusetts Institute of Technology in Cambridge, Massachusetts. As shown in Figure 1, the flume consists of a Plexiglas channel 23.1 meters in length, 60 cm in width, and 29 cm in depth. The channel is supported by a steel truss 23.2 meters long, 60 cm wide, and 67 cm high. The flume channel is supported 14 cm above the top of the truss framework by adjustable bolts which allow the channel to be leveled and plumbed with respect to the supporting framework. The truss is raised 80 cm above the floor, and is supported in three places: a central pivot support on which the framework tilts, and two screw jack supports on either side of the central support which permit variations in the channel slope. Each jack support consists of two screw jacks which are ganged by a chain-and-sprocket mechanism. The two pairs of jacks are connected by a drive rod so that they operate in unison to provide a uniform change in slope. The "central" pivot is not at the mid-point of the flume. It is 12.2 meters from the upstream end and 10.85 meters from the downstream end. At the upstream end of the channel is a covered section of the channel which makes up a headbox 90 cm long. Immediately downstream

from this is a plastic-tubing flow collimator. At the downstream end, the channel terminates in a rubber-lined metal channel which leads into the tailbox. The tailbox is made of epoxy-painted wood, with a steel framework.

Flow in the flume is produced by a five hp vertical propeller pump whose body is submerged in the tailbox. The pump lifts the water out of the tailbox and pumps it through an eight inch outlet, through a reducer and a discharge-controlling gate valve, into a 5 inch PVC pipe, which runs under the channel up the flume. At the upper end of the flume, the PVC pipe is joined by a rubber hose to a section of 5 inch acrylic pipe. The acrylic pipe is joined by another rubber hose to a Plexiglas flow expansion-manifold box. The outlet to the box consists of four 3 inch wire-reinforced rubber hoses which lead up into the bottom of the channel. A 3.410 inch orifice plate in the return line is used in conjunction with a 90 cm water-mercury differential manometer, to make measurements of discharge. In addition to the main flow outlet from the pump, there is a four inch bypass outlet, controlled by a valve, which allows the pump to run at full discharge, without having all the water pumped through the channel. The pump bearings are cooled by water pumped out of the tailbox, which is filtered by a fiberglass filter and then pumped into the bearings themselves. This process both cools and flushes the pump bearings. The flume is drained in two places: a tap

off the feed to the cooling pump from the tailbox, and another tap off of the main return line from the pump. An instrument carriage, running on rails mounted on the sides of the truss, provides a mount for the point gauge used to measure bed heights. The flume is of the recirculating type, designed so that sediment and water are constantly returned to the headbox as the flume runs. This means that the flow can reach sediment-transport equilibrium without having to add sediment constantly.

II. FLOW CONDITIONS AND MEASUREMENT PROCEDURE

All of the runs were made at flow velocities between 20 and 40 cm/sec. The flow depths ranged from 9 cm to 11 cm. At these velocities and flow depths, the conditions were well within the range defined by Southard (1971) for the production of ripples. The sediment used was a fine sand with a median grain size of 0.17 mm. For each run, the flume was filled to approximately the depth desired for the run and then started and allowed to run for 18 to 30 hours in order to reach equilibrium before commencing measurements. After each run, the flow was abruptly stopped so as to prevent the alteration of bed-forms by nonequilibrium flow and then carefully drained to permit a detailed examination of the bed. For the first five runs, the velocity was kept as nearly identical as possible. For each case, the manometer deflection was the same, and the flow depth was kept as close to 10.8 cm as possible to assure

constant velocity. Depth was measured by manual point gauge at the center point of the channel at the profiling station. The mean value of a series of water-height measurements was combined with the mean value of the bed height for the center point of the channel to yield the average depth cited in Table I. Measurements were taken before and after the run, as well as during it, to assure constancy. For the third through fifth runs, the flume was tilted up and then tilted down prior to the commencement of the run so that sediment would be transported from the upper end to the lower end of the flume. This caused the bed to be built up as the measurements were being made. For the last two runs, velocity was varied from the first series of runs. In the sixth run, it was high (about 30-35 cm/sec) and in the last run it was low (about 20 cm/sec). In the first series of runs, the sediment bed was allowed to dry completely so that sections could be cut in the bed and the internal structures formed there could be studied. The various runs are summarized in Table I, according to flow depth, velocity, aggradation and purpose. The first two runs (E2r and E3r) were made under equilibrium conditions, with no aggradation. These runs could be considered "control" runs. The next run (E4r) was the first run with aggradation. No results are listed because it was found that the flow was not uniform through the run due to a change in water depth through time. Runs G5r and G6r were made at the same flow depth and velocity as the E runs, but with the flume tipped to produce aggradation at the measuring

station. The idea of these runs was to give an indication of the type of synthetic internal structure produced by actual aggradation, to be compared with the equilibrium runs. The last two runs (H7r and J8r) were made at velocities different from the equilibrium runs so that the effects (if any) of changing velocity on internal structure could be observed. These last two runs could be compared to the equilibrium runs and to each other to permit the analysis of three different velocity changes.

The measurements taken consisted of bed-surface profiles. These profiles were made using a manual point gauge which measured the bed-surface height from an arbitrary datum level. For the early runs the profiles were taken at 1 cm intervals across a 25 cm section of the flume perpendicular to the flow, centered on the centerline of the flow to avoid effects due to the flume walls. In these profiles, the heights were measured to 0.01 cm. In the last two runs, the profiles were made only across the middle 20 cm of the flow and to a precision of 0.1 cm. This allowed a faster rate of data acquisition. Reading 25 points to a precision of 0.01 cm took a minimum of four minutes. Reading 20 points to a precision of 0.1 cm, on the other hand, took less than two minutes. Allowing for a brief delay between readings, the 25-point readings could be no less than six minutes apart. The 20-point profiles, on the other hand, could be made every four minutes. In both cases, as

TABLE I

RUN NUMBER	VELOCITY (cm/sec)	FLOW DEPTH (cm)	AGGRADATION	PURPOSE
E2r	24.1	10.8	no	equilibrium run
E3r	24.1	10.9	no	equilibrium run
E4r	19-22.4	11.6-13.7	yes	aggradation run
G5r	26.0	10.0	yes	aggradation run
G6r	24.7	10.6	yes	aggradation run
H7r	32.0	11.5	no	high velocity run
J8r	21.4	9.9	no	low velocity run

each bed-height measurement was made, it was reported to and recorded by an assistant. In the last two runs, longitudinal profiles were taken during the run along a 20 cm section of the channel. To insure the repeatability of the positioning of the point gauge for each transverse profile, a track was constructed on the instrument carriage with indentations every centimeter. The point gauge was mounted on a block which rode on the track. A pin protruding through the block lodged in the indentations, assuring the correct positioning of the point gauge. For the longitudinal profiles, the point gauge was held fixed on the instrument carriage, while the carriage was moved up the flume. The position of the carriage was carefully determined by a tape rule affixed to the instrument carriage track. Exact alignment of the carriage determined the precision of the positioning of the point gauge and the point of measurement.

III. DATA HANDLING: PLOTTING AND COMPARISON

Each flume run produced data in the form of numerical tables of bed heights. Each column of numbers represents a "digitalization" of the actual profile. These were plotted manually to produce a synthetic bed cross section. In plotting the data, the profiles were constructed as "time lines." If, at any point, the bed surface was eroded below a certain level, all profiles taken before that, which lay above that level, would be considered to be "eroded." On the other hand, any

profiles lying below that point would be plotted as being "buried." The final plot would be a series of time lines representing bed-surface profiles at certain fixed times, showing the various levels of erosion. This series of time lines would represent a synthetic cross section of the bed. It was the intention of the experimenter to couple the interval between profiles with the ripple migration rate. However, that rate was not determined during the runs, so there is no exact relationship between the ripple migration rate and the interval between profiles. Profiles were taken often enough so that there are more than enough to define the activity of each ripple as it passed through the sample section, even though the profiles do not necessarily define exactly the same point on each ripple.

In order to test the correlation of the synthetic bed cross sections with what structures actually formed in the flume, the bed was dried and sectioned in four of the seven runs made. In two of the runs for which sections were cut, flake graphite was added to the flow at intervals related to the profiling interval and allowed to settle on the bed. The graphite provided a "tracer" and caused the delicate lineation produced in the bed to be more visible. After drying and sectioning, the measurement section was photographed. After enlargement, these photographs could be directly compared to the synthetic cross sections produced by the profiles. To aid in

plotting and comparison, all plotting was done at the scale of 1 inch = 1 cm (2.54:1), and all photographs were enlarged to the same scale. For the purposes of the present work, comparison of photographs and data plots were restricted to qualitative criteria.

IV. DATA HANDLING: TRANSFORMATION

One especially valuable aspect of this new technique is the ability to manipulate the profiles mathematically. After the profiles had been constructed for the runs at equilibrium, several of them were "transformed." In this process, each individual profile (in numerical form) has a constant added to it. In a physical sense, this has the effect of raising the profile above those which came before it. This process simulates bed aggradation, a process which is difficult to actually perform in a flume. The idea behind this simulation is that it duplicates the behavior of a sediment bed in a natural environment in which deposition is taking place. Instead of a constant reworking of the same material, the lower levels of the bed are "buried" and protected from further sediment transport effects. This allows the preservation of any structures formed by moving bedforms. The runs in which the flume was tilted first up and then down were made so that actual aggradation could be observed and compared with synthesized aggradation.

RESULTS

I. PREDICTION OF EXPECTED RESULTS

For the synthetic construction of internal bed structures to be useful, it must be possible to show that the structures produced are realistic and representative. What is necessary, therefore, is a test of the qualitative similarity of the synthetic structures and real structures produced in a flume. The studies of natural environments, and those made in flumes, suggest that the structures one should expect to see produced by migrating ripples would be small-scale trough cross-stratification. It is necessary, in order to test the technique, to show the production of trough cross-bedding. In addition, a comparison should be attempted between the synthetic structures produced and any real structure formed in the flume. The simplest way of demonstrating the comparability of the synthetic structures and the real structures is to construct the synthetic structures and then cut and section the sediment bed at the point of measurement and photograph the section. A direct comparison between the photograph and the synthetic profile will immediately reveal the validity of the technique. The photograph of the section will also confirm (or deny) the creation of trough cross-bedding by ripples. In order to simplify the interpretation of the photographs, some sort of tracer should be added to the bed so that any internal

structure will be highlighted.

After the verisimilitude of the technique has been demonstrated, an application of the technique should be attempted, so that its usefulness can be demonstrated. For this, a comparison photograph is not necessary, as the intention is to show how the technique responds to changes in flow conditions or how the introduction of a "transformation constant" can alter the synthetic structures produced by the technique. An additional benefit of the technique is that it may enable the mechanics of structure formation to be more fully examined.

II. SYNTHESIS - PHOTOGRAPH COMPARISONS: EQUILIBRIUM RUNS

The first goal of this experimental study was the testing of the verisimilitude of the structures synthesized. Figures 2a and 2b are the synthetic plot and corresponding photograph for the first test run. Both of these give some indication of the trough cross-stratification produced by migrating ripples. The photograph does not show the detail visible in the synthetic plot, but the general correlation is visible, especially along the left-hand side of the plot. In the central portion, some noticeable lineation is visible in the photograph, but it forms the base of the section studied by the synthesis technique. It should be noted that both the plot and the photograph are at the same scale.

The second pair of figures (Figs. 3a and 3b) are the product of the second test run. For this run, flake graphite was introduced into the flow at intervals corresponding to the profiling intervals. Wetted graphite was added to the flow, upstream of the sample section, at intervals of three profiles. The graphite settled onto the bed allowing better definition of the real structures. The photograph for this run, Figure 3b, shows the effect of the graphite as dark bands, delineating the structure. Once again, the synthetic profile occupies only the upper portion of the bed. This is indicative of the amount of reworking of the sediment bed involved in the migration of ripples at equilibrium in the flume. Since there was no net buildup of the bed, the ripples kept eroding and depositing at the same level. The only structure visible is due to an extraordinarily deep erosion by some ripples, which remains when buried. The long, unstratified zone at the top of the section, on the left-hand side, is due to the advance of a ripple crest between the next-to-last and the last profiles. This indicates that the surface profile should be disregarded, as it is not a true representation of internal structure. It is useful to have the surface profile in comparing the synthesis to the photograph, as it can be matched up exactly. Any reliance on the surface profile in regard to internal structure, however, will only cause misinterpretation.

III. SYNTHESIS - PHOTOGRAPH COMPARISONS: AGGRADING RUNS

In order to be able to examine the formation of internal structure more fully, it was judged desirable to make flume runs in which some amount of bed aggradation was produced. The synthetic structure shown in Figure 4a and the photograph which is Figure 4b are the products of the first of these runs. What is immediately visible is the increased amount of structure preserved, even though the total net buildup of the bed was on the order of 2 cm. This amount of aggradation was produced by tilting the flume so that the bed was eroded at the upper end of the flume and deposited downstream. Profiles were taken at a point just downstream from the central pivot so that the water depth would remain constant in spite of the altered slope of the flume. The scale of the aggradation was slightly larger than the scale of the ripples involved, so that there is better preservation of the internal structure. Graphite again was used to accentuate bed features in the photograph, but it was used more sparingly (only every tenth profile). The structure which is visible in both the synthetic section and the real section is unmistakably trough cross-bedding. This is exactly what one should expect to find in a sediment bed which has been modified by migrating ripples. In addition, there is very close, if not exact, agreement between the lines on the synthetic section and the graphite-enhanced structure in the photographed section. In one set of figures,

therefore, the correlation between structures formed in real flows and flumes and the verisimilitude of the synthesis technique for producing artificial structures have both been demonstrated. Another run, duplicating these results, was made also, and the section and photograph make up the next two figures (Figs. 5a and 5b). Again, the match between the two shows the validity of the technique. For this last photographic run, graphite was not introduced into the flow, because it was felt that too much graphite might build up in the sediment, obscuring the structure formed during the run. In spite of this, there is still delineation of the structure by the graphite from preceding runs, so a great deal of structure is visible.

IV. PROFILING RUNS: APPLICATION OF THE TECHNIQUE

After the runs had been made which showed that the synthesis technique worked, it was deemed advisable to make some additional runs to show how the technique could be applied to sedimentology in general. To further this end, two runs were made, one at a lower velocity than the original tests, the other at a higher velocity. In addition, there were two sets of profiles taken for each run: one transverse and one longitudinal with respect to the flow direction. These profiles are shown in the next four figures (Figs. 6a, 6b, 7a, and 7b). Figure 6a shows the transverse profile taken during

the higher velocity run. Figure 6b is the corresponding longitudinal profile. Figure 7a is the transverse profile from the slower run, while Figure 7b is the matching longitudinal profile. In comparing these profiles, it should be noted that the profiling intervals were not matched to the ripple migration rate, so there is no exact match to the ripple migration rate, and, therefore, no exact match-up of the profiles. What is evident, especially in the longitudinal profiles, is the nature of the shape of the ripples. The actual ripples which were responsible for these profiles are shown in photographs taken during and after the runs. Figures 8 and 9 show the ripples formed by the lower-velocity run, while Figures 10 and 11 show the ripples present in the higher-velocity run. The actual differences are difficult to make out in the photographs, but in the profiles the distinguishing features stand out more clearly. The low-velocity ripples seen in Figure 7b seem to have sharper crests, leaving steeper cross-bedding than the high-velocity flow. This is evident also in the transverse profiles Figures 6a and 7a, but not to such a great extent. A further comparison can be made between these profiles and the transverse profiles made for the earlier test runs. These show slope angles intermediate between the "slow" and "fast" runs. It may be stated, therefore, that the slope angle of cross-bedding, viewed transverse to flow direction, can be related to flow velocity. An additional observation made during the runs confirms the statement made earlier that

the shape of the troughs in the cross-bedding was due to the shape of the scour surface of the ripple. In fact, the majority of structures visible in the sections are directly related to those scour surfaces. An in-depth analysis of the nature of sediment transport responsible for the change in feature shape with velocity is out of place here. Suffice it to say that it appears that sediment transport involves a higher percentage of bed-load movement at lower velocities than at higher velocities, where suspended load becomes more important. Under low-velocity conditions, the movement of sediment grains up stoss slopes and down slip faces of ripples would determine the shape of structures. This implies that the angular relationships in the structures formed at low velocities would depend more on the angle of repose of the sediment than would structures formed at higher velocities. This effect would act in addition to the effects of flow velocities on the geometry of the ripples themselves. It should be noted here that the exact differences in structures caused by the alteration of flow conditions are not explicitly determinable. In fact, the variability between runs made under the same flow conditions can be significant (compare the profiles from runs E2r and E3r, made under nearly identical flow conditions). The physical processes responsible for the production of ripples are such that it is impossible to duplicate a specific suite of ripples, in spite of exact duplication of flow conditions. This means that it is technically impossible to define exactly

what changes in structure are due to changes in flow conditions and what changes are due to simple variability between ripples. The most feasible approach to a solution for this problem is a statistical analysis of a readily definable set of ripple characteristics over a large enough sample of ripples to assure statistical validity. Analyses such as this for ripples formed under constant or varying flow conditions can yield an idea of what variability actually is due to changes in flow conditions. It is now possible to see several benefits derived from the ability to synthetically produce bedforms, but there are still more.

V. DATA MANIPULATION: SYNTHETIC AGGRADATION

As stated earlier, one drawback to flume work has been the limitations placed on the amount of bed buildup which is feasible. If sediment is added to the bed in any large amount, the flume channel becomes filled with sediment and the water overflows the top of the channel. In order to maintain a reasonable flow depth, the amount of sediment which can be added to the bed is, therefore, quite limited. While it might be possible to build the channel deeper, this would necessitate the strengthening of the supporting framework of the flume. This would cause the framework to become increasingly unwieldy. In addition, as mentioned earlier, the addition of sediment to the flume is a difficult process. It is physically difficult to dump sediment into the flume evenly and at an exactly uniform rate. As shown in the earlier runs of this project,

reworking of the bed erases most features, and the amount of real aggradation possible is limited to approximately the scale of the bedforms under scrutiny. This means that the availability of a method for artificially building up the bed would greatly expand the usefulness of flume studies of bedforms. It is, therefore, very fortunate that the new technique for the construction of synthetic structures also lends itself to the production of synthetic bed aggradation. The process used for synthesizing aggradation is quite simple. A "transformation constant" is added to every bed-height measurement. A time constant added to the transformation assures that there is a steady buildup of the base level (the datum on which the bed-height profiles are based). This "lifts" each profile slightly with respect to the one before it. In turn, this produces a new section which is representative of what should be seen under real conditions of bed aggradation. The results of the application of such a transformation are shown in the next group of figures (Figures 12 through 13b). These are all longitudinal profiles, as an attempt was made to duplicate the classic "climbing ripple" structure. Although the high-velocity run reveals little internal structure, it does show a very-low-angle rate of climb (at an aggradation rate of 0.25 cm/hr). The low-velocity run plot (Figure 13a), since it represents a longer period of time and shows the structure in more detail, shows the angle of climb to be about seven degrees (again at a 0.25 cm/hr rate of aggradation). Another plot, made at 0.5 cm/hr,

is seen in the next figure (Fig. 13b). It shows the low-velocity ripples climbing at a higher angle (about fifteen degrees). The comparison between these synthetic structures and those which have been produced in the laboratory, and observed in the field, is rather striking. It should be noted here that this is not a completely definitive test of the technique. In order to show that the synthesis works exactly, it would be necessary to produce several sets of identical ripples, under exactly the same flow conditions, in runs with and without aggradation. This would demonstrate the effects (if any) on the structures caused by the aggradation. Unfortunately, it is impossible to duplicate exactly a suite of ripples, no matter how exactly the flow conditions are matched. Therefore, the only way to examine the effects of aggradation on structure geometry would be the very tedious compilation and statistical comparison of a set of bedform and structure characteristics. These characteristics could be ripple index, radius of curvature of crests or troughs, or any other distinguishing features which might be found. For the purposes of this paper, it has been shown, by a comparison of the results from runs E2r and E3r (the control runs) with those from runs G5r and G6r (the aggradation runs) that the structures produced are qualitatively similar, in spite of the fact that aggradation took place during the last two runs. It can therefore be assumed that the effects of aggradation are small enough that they are concealed by the variations between the ripple suites formed in the various

flume runs. An additional effect, which was not addressed by the aggrading runs, was the difference, or possible difference, in the way the aggradation took place. For the two aggradation runs, G5r and G6r, the sediment discharge varied with distance down the flume, since the bed was being planed off at the upstream end and material was being deposited downstream. The other possibility is that material could have been added to the bed from outside the flume. This would have caused a change in the sediment concentration through time. Whether there might be effects caused by the differences between these two techniques for adding sediment to the flume is unknown. It would appear that the total difference between the presence or absence of aggradation is very small, as stated above. Any difference between these two aggradation methods, therefore, is also assumed to be small. It therefore appears that a very useful technique for the synthesis and analysis of internal bed structures has been demonstrated.

CONCLUSIONS

What has been discussed here is the demonstration, testing, and application of a new technique for the synthetic construction of internal bed structure. The technique uses the combination of a series of time-line bed-height profiles to produce a reasonable facsimile of the structure which could be expected to form under given conditions of fluid flow and sediment transport. In this particular case, the technique has been applied to the formation of trough cross-bedding by migrating ripples. By examining this fairly well known case, it has been shown that the method does, indeed, produce structures which agree with the structures actually formed in the flume, and which also agree with data taken from previous works. In addition, the method has been shown to be useful in duplicating expected sedimentary structures under conditions which are difficult to achieve in a flume. By the application of a transformation constant, it has been possible to simulate bed buildup without filling the flume with additional sediment. This means that a more realistic picture can be developed of what types of structures form under what bedforms. An additional benefit is that this technique allows a very careful analysis of the production of internal structures and the variance of internal structure with changing flow conditions and bedform shapes. That this new method works in a flume is also especially useful in that it allows very precise control of the variables which

govern bedform behavior. Such control permits the correlation of flow variables with internal bed structures on a direct basis. As noted, the tests performed on the technique are not completely definitive, but the results do show excellent qualitative agreement for the tests made. These conclusions indicate that a simplified technique with far-reaching implications for sedimentology and geology as a whole has been established with sufficient validity to warrant continued application and development.

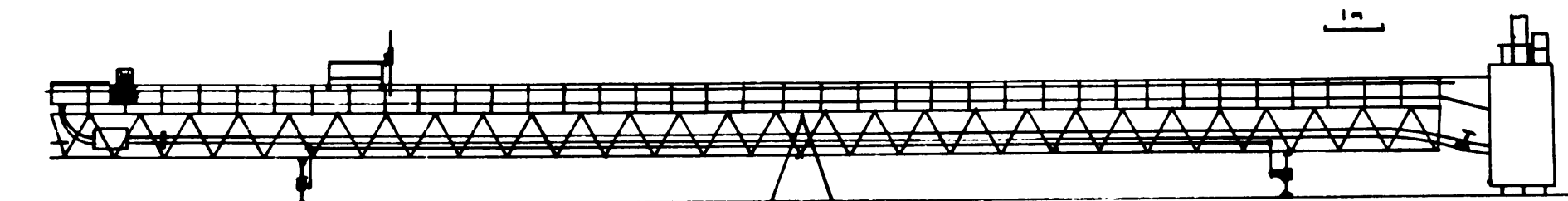


Figure 1. Diagram of the 23-meter flume.

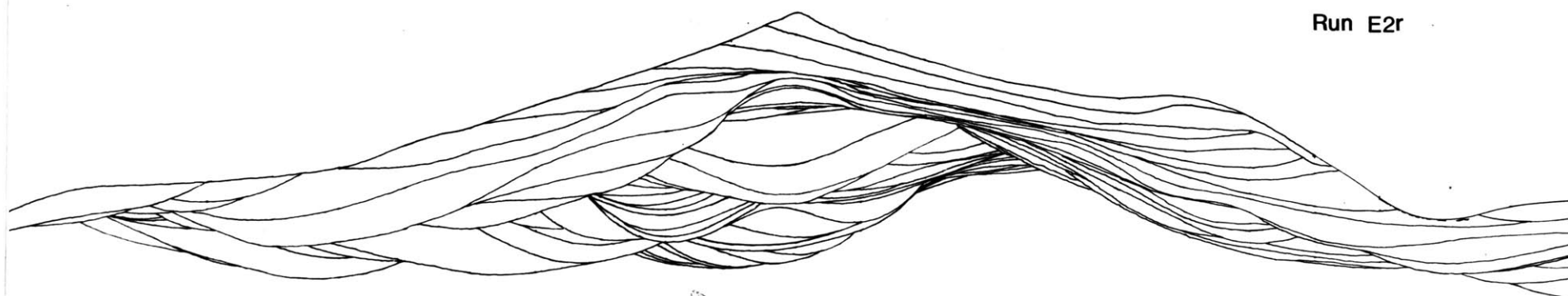


Figure 2a. Synthetic structures produced in Run E2r.

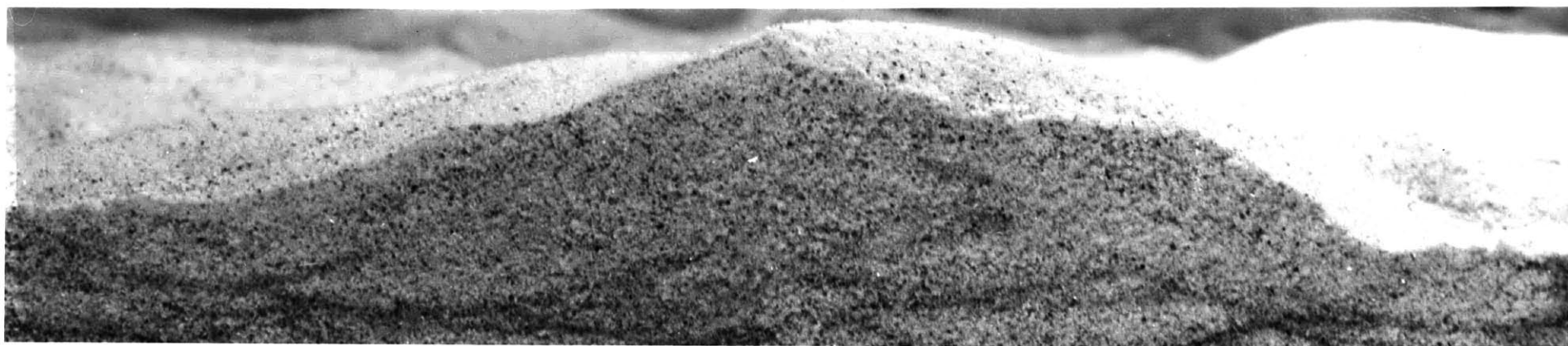


Figure 2b. Photograph of actual bed structures, Run E2r.



Figure 3a. Synthetic structures produced in Run E3r.



Figure 3b, Photograph of actual bed structures, Run E3r.

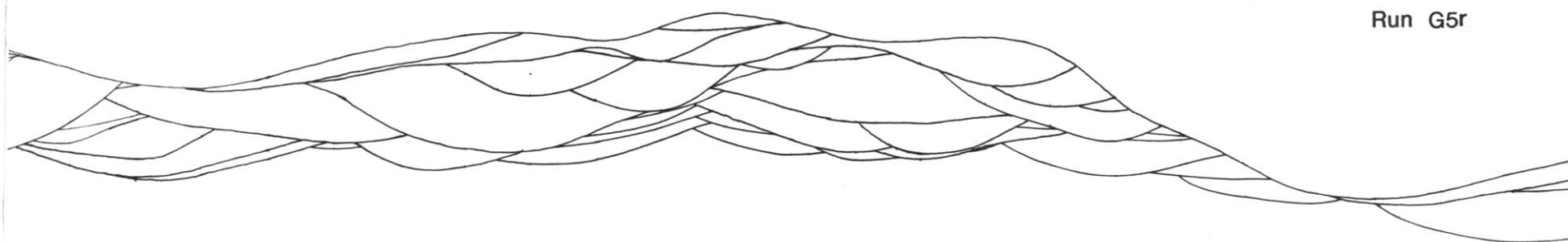


Figure 4a. Synthetic structures produced in Run G5r.

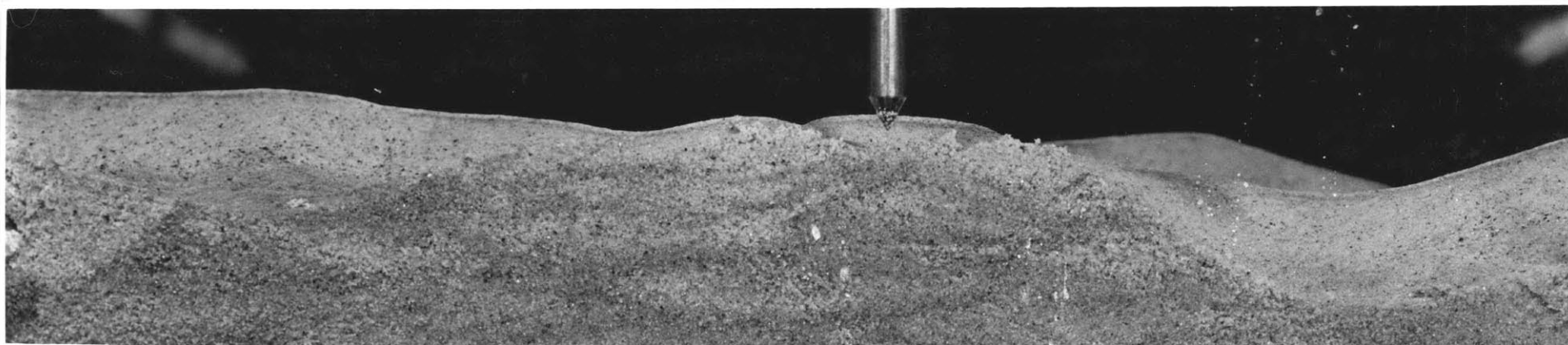


Figure 4b. Photograph of actual bed structures, Run G5r.

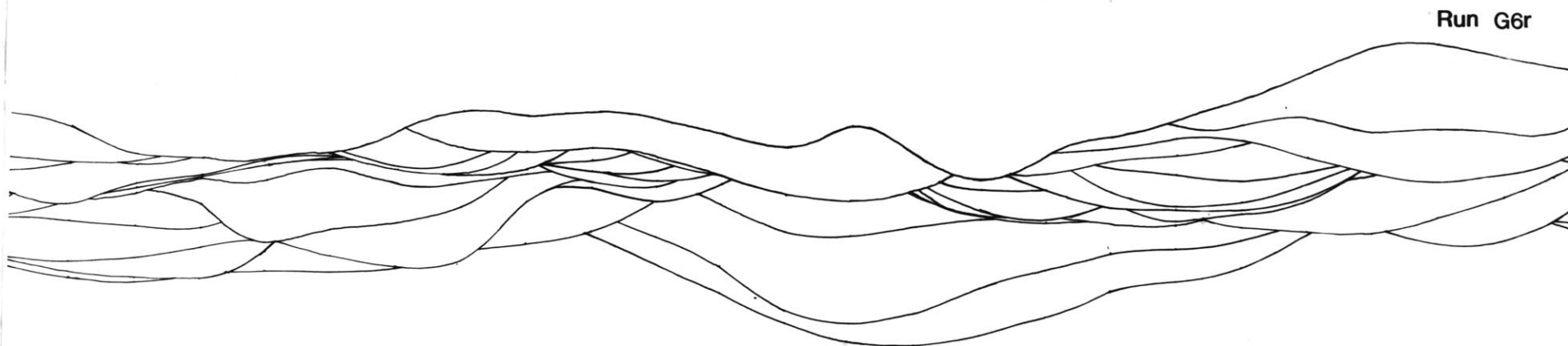


Figure 5a. Synthetic structures produced in Run G6r.

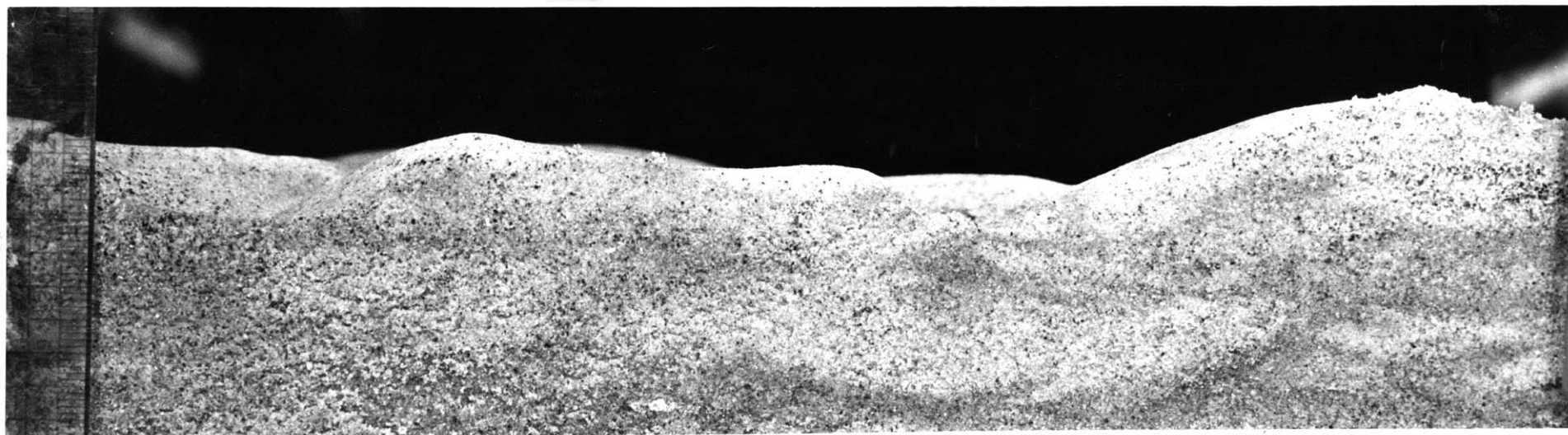


Figure 5b. Photograph of actual bed structures, Run G6r.

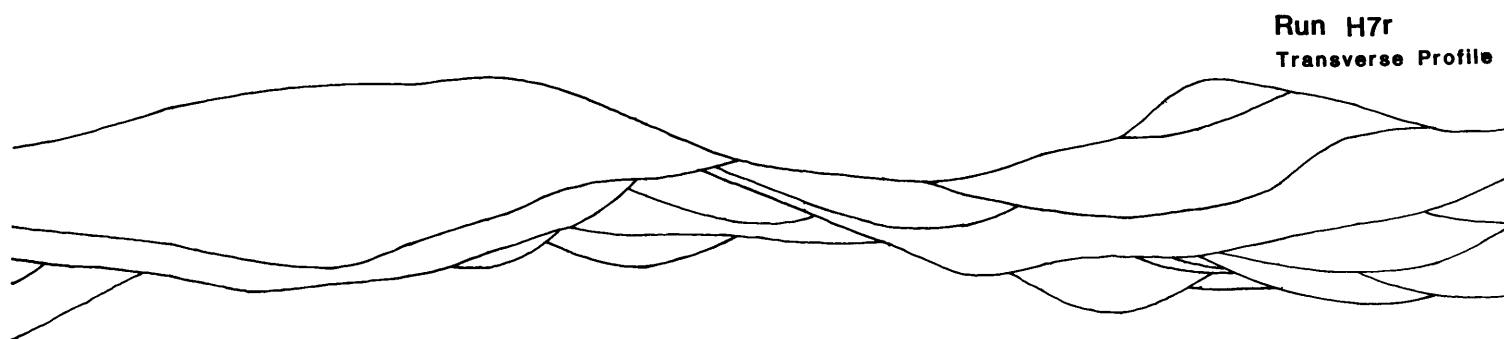


Figure 6a. Synthetic transverse profile, Run H7r.

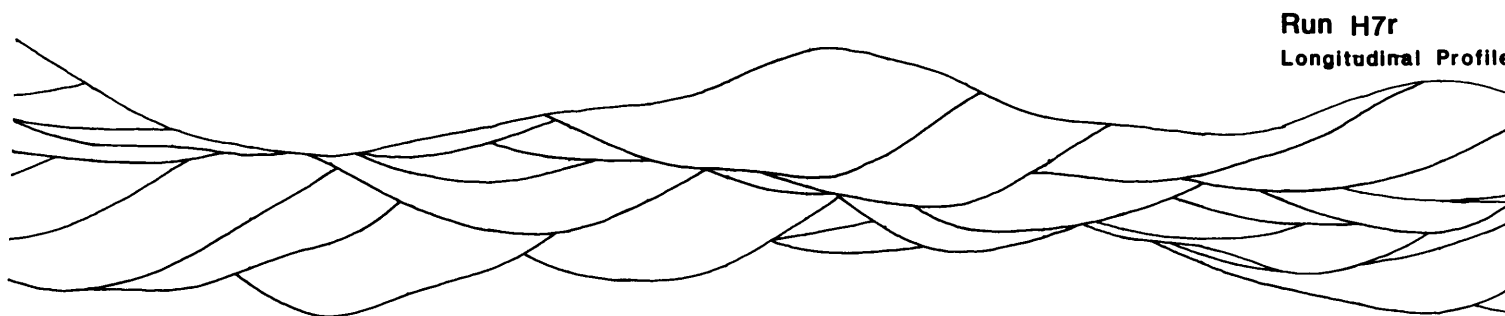


Figure 6b. Synthetic longitudinal profile, Run H7r.

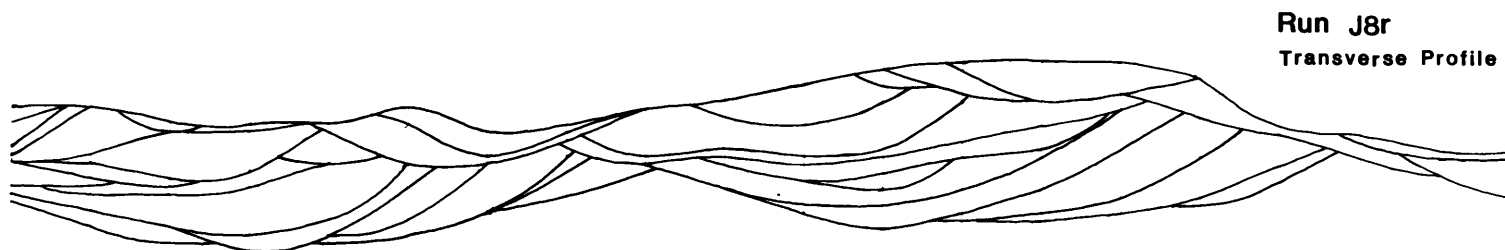


Figure 7a. Synthetic transverse profile, Run J8r.

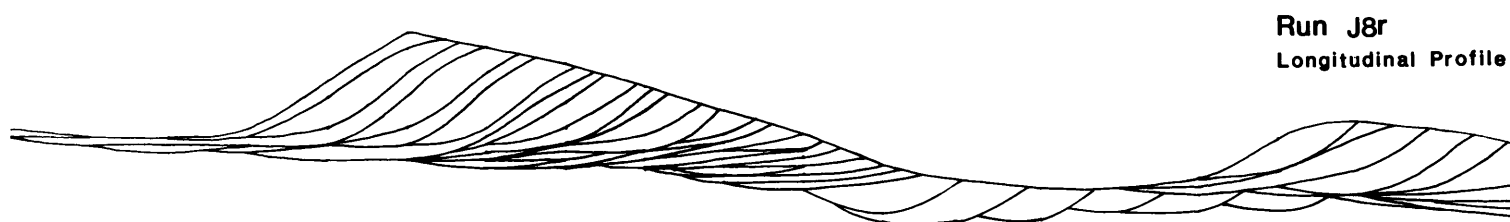


Figure 7b. Synthetic longitudinal profile, Run J8r.



Figure 8. Photograph of ripples formed during Run J8r.



Figure 9. Photograph of ripples formed during Run J8r.

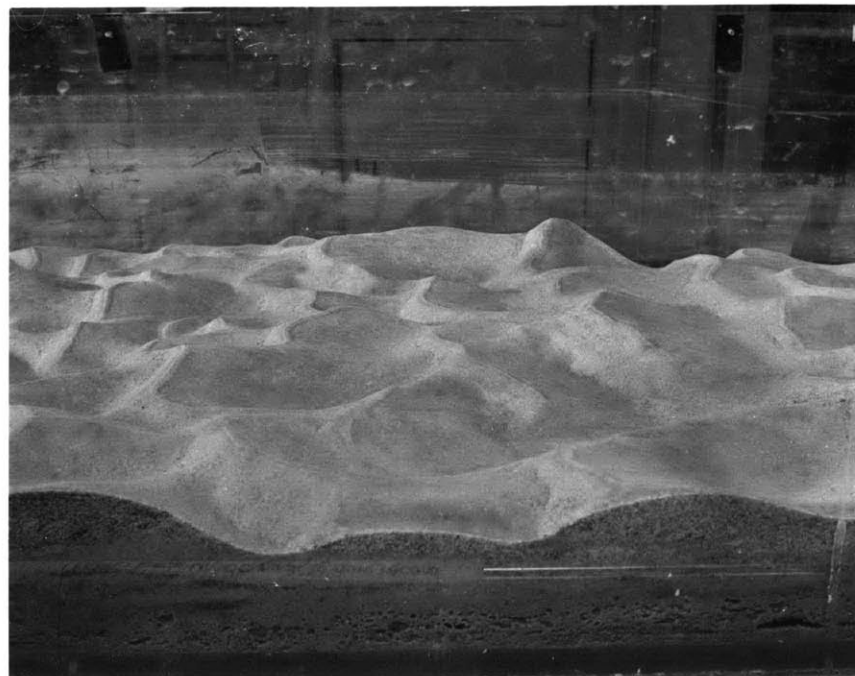


Figure 10. Photograph of ripples formed during Run H7r.



Figure 11. Photograph of ripples formed during Run H7r.

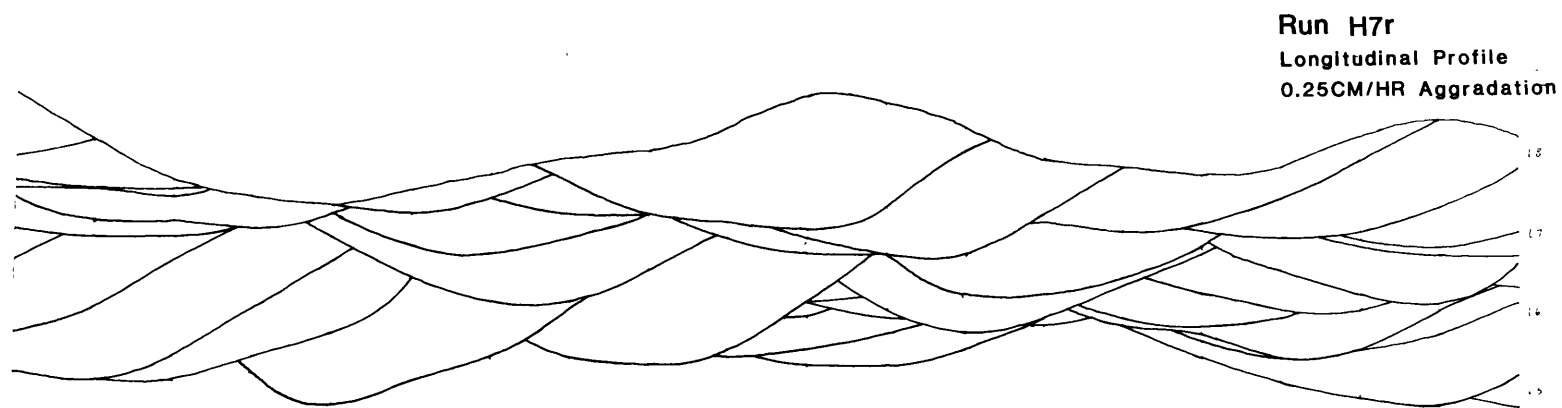


Figure 12. Synthetic longitudinal profile, Run H7r,
0.25 cm/hr aggradation superimposed.

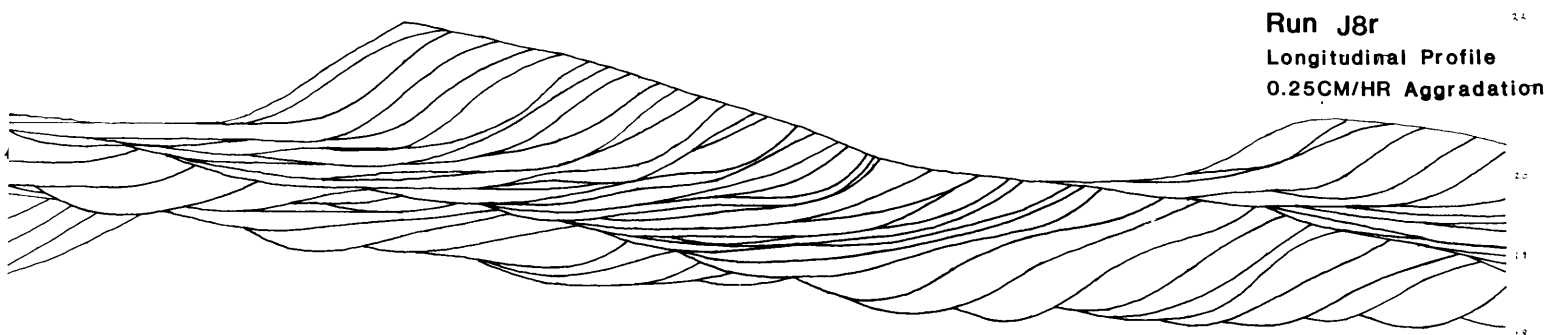


Figure 13a. Synthetic longitudinal profile, Run J8r,
0.25 cm/hr aggradation superimposed.

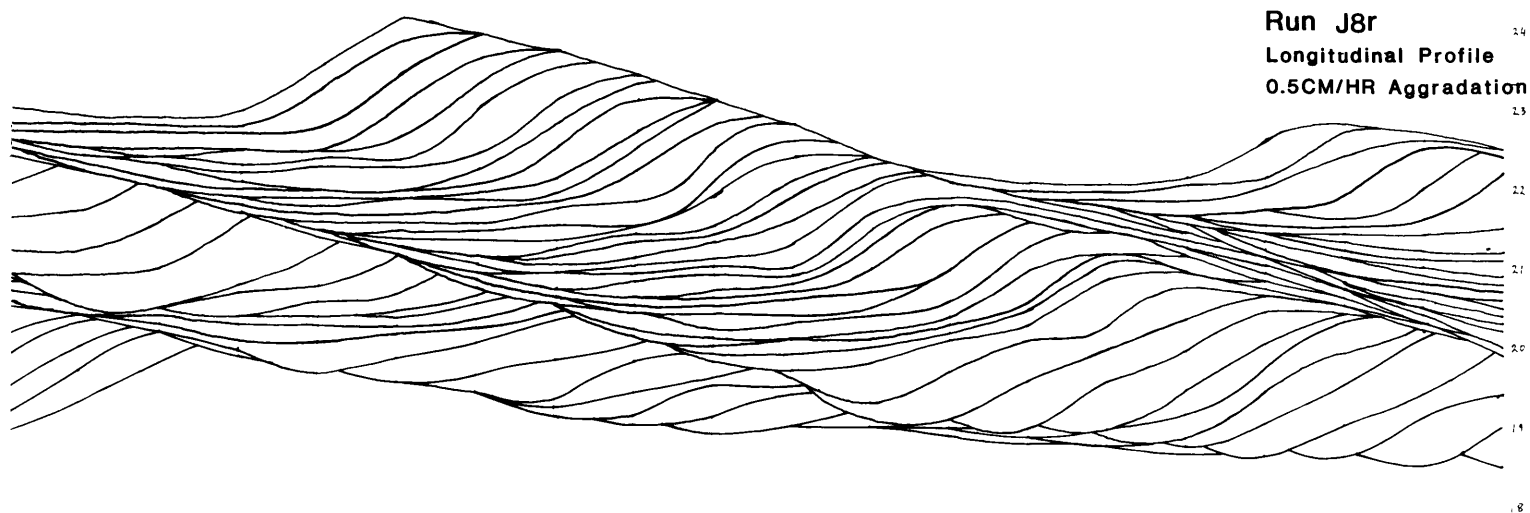


Figure 13b. Synthetic longitudinal profile, Run J8r,
0.5 cm/hr aggradation superimposed.

REFERENCES CITED

- ALLEN, J.R.L., 1963a, Henry Clifton Sorby and the sedimentary structures of sands and sandstones in relation to flow conditions, *Geologie en Mijnbouw*, 42e, 223 - 228.
- _____, 1963b, The classification of cross-stratified units, with notes on their origin, *Sedimentology*, 2, 93 - 114.
- BRUSH, L.M., JR., 1958, Study of cross-stratification in a large laboratory flume, *Bull. Geol. Soc. Am.* v. 69, 1542.
- COLEMAN, J.M. and GAGLIANO, S.M., 1965, Sedimentary structures: Mississippi River deltaic plain, *Soc. Econ. Paleo. Min. Spec. Pub.*, 12, 133 - 148.
- _____, and WEBB, J.E., 1964, Minor sedimentary structures in a prograding distributary, *Mar. Geol.*, v. 1, 240 - 258.
- COTTER, E., 1971, Paleoflow characteristics of a late cretaceous river in Utah from analysis of sedimentary structures in the ferron sandstone, *Jour. Sed. Pet.*, v. 41, 129 - 138.
- DOEGLAS, D.J., 1962, The structure of sedimentary deposits of braided rivers, *Sedimentology*, v. 1, 167 - 190.
- FÜCHTBAUER, H. and MÜLLER, G., *Sedimente und Sedimentgesteine*, E. Schweizerbart'sche Verlagsbuchhandlung: Stuttgart, 1970.
- GUY, H.P., SIMONS, D.B., and RICHARDSON, E.V., 1966, Summary of alluvial channel data from flume experiments, 1956 - 1961, *U.S. Geol. Surv. Prof. Paper* 462-I, 96 p.
- HARMS, J.C., 1969, Hydraulic significance of some sand ripples, *Geol. Soc. Amer. Bull.*, v. 80, 363 - 396.
- _____, and FAHNESTOCK, R.K., 1965, Stratification, bed forms, and flow phenomena (with an example from the Rio Grande), *Soc. Econ. Paleo. Min. Spec. Pub.*, 12, 84 - 115.
- _____, MACKENZIE, D.B., and MCCUBBIN, D.G., 1963, Stratification in modern sands of the Red River, Louisiana, *Jour. Geol.*, v. 71, 566 - 580.

- HARMS, J.C., SOUTHARD, J.B., SPEARING, D.R., and WALKER, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences, Soc. Econ. Paleo. Min. Short Course 2, 161 p.
- IMBRIE, J. and BUCHANAN, H., 1965, Sedimentary structures in modern carbonate sands of the Bahamas, Soc. Econ. Paleo. Min. Spec. Pub., 12, 149 - 172.
- JOPLING, A.V., 1960, An experimental study on the mechanics of bedding, Ph.D. Thesis, Harvard University, 358 p.
- _____, 1965, Laboratory study of the distribution of grain sizes in cross-bedded deposits, Soc. Econ. Paleo. Min. Spec. Pub., 12, 53 - 65.
- _____ and WALKER, R.G., 1968, Morphology and origin of ripple-drift cross-lamination, with examples from the pleistocene of Massachusetts, Jour. Sed. Pet., v. 38, 971 - 984.
- MASTERS, C.D., 1967, Use of sedimentary structures in determination of depositional environments, Mesaverde formation, Williams Fork Mountains, Colorado, Am. Assoc. Pet. Geol. Bull., v. 51, no. 10, 2033 - 2043.
- MCKEE, E.D., 1965, Experiments on ripple lamination, Soc. Econ. Paleo. Min. Spec. Pub., 12, 66 - 83.
- _____, 1957, Flume experiments on the production of stratification and cross-stratification, Jour. Sed. Pet., v. 27, no. 2, 129 - 134.
- _____, 1957, Primary structures in some recent sediments, Bull. Amer. Assoc. Pet. Geol., v. 41, no. 8, 1704 - 1747.
- _____, 1966, Significance of climbing-ripple structure, Geo. Surv. Res., D94 - D103.
- MIDDLETON, G.V., 1965, Antidune cross-bedding in a large flume, Jour. Sed. Pet., v. 35, no. 4, 922 - 927.
- PELLETIER, B.R., 1965, Paleocurrents in the triassic of Northeastern British Columbia, Soc. Econ. Paleo. Min. Spec. Pub., 12, 233 - 245.
- REINECK, H.E. and SINGH, I.B., Depositional Environments, Springer-Verlag: New York, 1975.

- SIMONS, D.B., RICHARDSON, E.V. and ALBERTSON, M.L., 1961, Flume studies using medium sand (0.45 mm), Geological Survey Water-Supply Paper 1498-A. Washington: United States Government Printing Office.
- _____ and NORDIN, C., 1964, Sediment structures generated by flow in alluvial channels, Amer. Assoc. Pet. Geol., v. 48, 547.
- _____ and NORDIN, C.F., JR., 1965, Sedimentary structures generated by flow in alluvial channels, Soc. Econ. Paleo. Min. Spec. Pub., 12, 34 - 52.
- ✓ SOUTHARD, J.B., 1971, Representation of bed configurations in depth-velocity-size diagrams, Jour. Sed. Pet., v. 41, no. 4, 903 - 915.
- _____ and BOGUCHWAL, L.A., 1973, Flume experiments on the transition from ripples to lower flat bed with increasing sand size, Jour. Sed. Pet., v. 43, no. 4, 1114 - 1121.
- _____ and HARMS, J.C., 1972, Sequence of bedform and stratification in silts, based on flume experiments, Amer. Assoc. Pet. Geol., v. 56, 654.